Construction and Building Materials 48 (2013) 424–433

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Design of masonry blocks with enhanced thermomechanical performances by topology optimization

Matteo Bruggi, Alberto Taliercio *

Department of Civil and Environmental Engineering, Politecnico di Milano, I20133 Milano, Italy

HIGHLIGHTS

- Original application of topology optimization to the design of masonry blocks.
- Combined optimization of thermal and mechanical performances of masonry blocks.
- Achievement of non-trivial block layouts, depending on the design constraints.

ARTICLE INFO

Article history:
Received 18 October 2012
Received in revised form 4 July 2013
Accepted 16 July 2013
Available online 7 August 2013

Keywords:
Block masonry
Thermal conductivity
Topology optimization

ABSTRACT

The problem of maximizing the thermal insulation of buildings is dealt with, by determining the geometry of masonry blocks that minimizes the transmittance of any wall. Assuming the heat flux to be uniform across the wall surfaces, topology optimization is employed to define the layout of the block section. Constraints on the block stiffness are also prescribed. The presence of holes of given shape in any prescribed position and other technological constraints can be easily embodied in the optimization procedure. The effect of the design constraints on the optimal layout of the blocks is investigated. The thermal efficiency of the optimized units is also compared with that of commercially available blocks.

1. Introduction

One of the primary goals in the field of modern construction is to design buildings with high thermal performances. This is dictated primarily by the need of reducing energy consumption in the exploitation of the building, because of the progressive decrease in available energy sources and the need of limiting the emissions of pollutants. This can be achieved by properly defining exposure and/or shape of the building, optimizing technological systems, using large transparent walls to increase lighting and passive heating, as well as materials and construction elements that minimize the heat flows between the interior and the exterior of the building.

Recently, much attention has been devoted by several researchers to the use of wastes of different nature (PET bottles or rubber tires [1], fabrics [2], corn cobs [3], etc.) to enhance the thermal insulation properties of building materials, typically concrete. These wastes can be added to the concrete mix in the form of shreds, or used to fill air boxes in multileaf walls.

In this paper, attention is focused on the optimal design of the shape of masonry (or concrete) units in order to minimize their thermal transmittance (i.e., to maximize their thermal resistance), using the mathematical tool of topology optimization. The 'thermal transmittance' (usually denoted by U) of any wall is the heat flow per square meter, divided by the difference in temperature between the faces of the wall itself; accordingly, it is expressed in W/m^2 K.

Several authors have addressed the problem of finding the optimal geometry of a masonry block that allows the thermal insulation of any building to be maximized. Al-Jabri et al. [4] carried out an experimental investigation on the thermal insulation properties of lightweight concrete hollow blocks. In their study, the authors refer to a similar previous research program [5] in which 13 kinds of hollow blocks with different hole geometry (aligned and staggered) were developed, and their thermal and strength properties were analyzed. Extensive numerical investigations were carried out by del Coz Díaz et al. with the aim of providing improved layouts for a wide class of structural elements (in particular, heat–insulating lightweight concrete hollow brick walls [6] and slabs floors [7], taking into account the nonlinearity deriving from radiation effects [8,9]). In these works, the information generated by finite element analyses is employed to select the optimum design among a number of alternative constructive possibilities.

---

* Corresponding author. Tel.: +39 0223994241; fax: +39 0223994220.
E-mail addresses: matteo.bruggi@polimi.it (M. Bruggi), alberto.taliercio@polimi.it (A. Taliercio).

0950-0618/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.conbuildmat.2013.07.023

Nomenclature

b	heat energy per unit volume, W/m^3
$\mathcal{C}^S$, $\mathcal{C}^T$	structural and thermal compliances
$\mathcal{C}^S_h$	structural compliance for the hth load case
$\mathcal{C}^S_{0h}$	structural compliance of the solid design domain for the hth load case
E	Young's modulus
h_c (h_{ci}, h_{co})	convective heat transfer coefficient (with inner/outer environment), W/(m^2 K)
$\underline{\underline{H}}_t$	finite element transfer matrix
k, $\underline{\underline{k}}$	thermal conductivity (scalar and tensor), W/(m K)
k_0, k_1	bounds for the thermal conductivity ($k_0 < k_1$)
$\underline{\underline{K}}_s$, $\underline{\underline{K}}_t$	finite element stiffness and conductivity matrices
q_c	heat flux per unit area, W/m^2
T	temperature field
T_0	prescribed boundary temperature
T_a (T_{ai}, T_{ao})	ambient temperature (inner/outer)
U	thermal transmittance (or heat transmission coefficient), W/(m^2 K)
$\underline{U}$	array of the nodal displacements
V_f, $\overline{V}_f$	percentage of voids, maximum allowable percentage of voids
w	virtual temperature field
$\underline{x}$	array of the finite element densities (design variables), x_i
$\tilde{x}_i$	filtered design variables

Greek symbols

α_i	$= \mathcal{C}^S_h \big/ \mathcal{C}^S_{0h}$
Γ_c, Γ_f, Γ_T	parts of the boundary of the design domain on which convective heat transfer, heat flux, or temperature are prescribed, respectively
$\partial\Omega$	boundary of the design domain
$\underline{\theta}$	array of the nodal temperatures
ν	Poisson's ratio
ρ	material density
Ω	design domain

Experimental researches aimed at assessing the influence of the material properties on the thermal efficiency of masonry units were carried out, e.g., by Bastos et al. [10], who correlated the mix design with different properties of lightweight concrete masonry blocks, including compressive strength and thermal conductivity. Topçu and Isikdağ [11] focused on the influence of pearlite in the reduction of the thermal conductivity of bricks; note, however, that pearlite decreases the mechanical strength of the units. Ünal et al. [12] carried out an experimental study on concrete blocks with different amounts of cement and diatomite, and showed that thermal conductivity decreases as the percentage of diatomite increases. Also the presence of air cells in concrete units and mortar joints affects the thermal conductivity of a wall, as evaluated by Abdou and Murali [13] through tests on three walls.

The effects of the thermal properties of the different constituent materials and the dimensions of the recesses on the overall thermal performances of several structural components (floors made up of clay, concrete and lightweight concrete hollow blocks [14], multi-holed lightweight concrete blocks [15,16]) were investigated by del Coz Díaz and coworkers. The same authors also carried out experiments focusing on the hygrothermal properties of different mixes of lightweight concrete that are commonly employed in the fabrication of blocks making up the building envelope and provided best fitting numerical studies [17].

Recently, Sousa et al. [18,19] have used a genetic algorithm for the definition of the geometry of lightweight concrete blocks that minimizes their transmittance, by determining the optimum values of a finite number of parameters that define the position, the size and the spacing of the holes within the block. The holes are assumed to be of rectangular shape and arranged in a regular mesh, either aligned or staggered.

The present work deals essentially with the same problem studied in [18,19], but with a more general approach. No a priori assumption is made about the geometry of the holes in the block, so as to fully exploit the potentials of topology optimization. Indeed, this technique consists in determining the optimal distribution of a prescribed amount of material over a fixed domain, to maximize the performances of any body (see e.g. [20]). Topology optimization differs from shape optimization, as the final topology of the design domain generally differs from that of the domain at the beginning of the optimization process. Unlike shape optimization, topology optimization allows material layouts characterized by voids and multiply connected regions to be obtained, even if the original design domain is simply connected: accordingly, it is an extremely flexible design tool.

Many authors have used topology optimization to maximize the stiffness or strength properties of bi-and three-dimensional bodies. A broad and updated survey of the established numerical methods developed in structural topology optimization can be found in [21]. An interesting application of topology optimization to the definition of the optimal shape of innovative hollow concrete masonry blocks is presented in [22], in which new layouts are proposed characterized by reduced weight, adequate strength, and enhanced handling possibility.

A different, fertile area of research involves thermal problems. Most of the formulations developed so far address the problem of the optimal conductor, i.e. the achievement of the topology that maximizes heat transfer for an assigned volume constraint under steady-state assumption. This was done e.g. in [23], where the Evolutionary Structural Optimization (ESO) framework to conduction-dominated thermal applications is implemented. The same optimization technique can be used to address temperature reduction of heat conducting fields [24].

Recent trends in civil and mechanical engineering show an increasing interest towards the themes of sustainable design and energy saving, especially in the area of building technology. On this theme, in [25] the optimal design of thin insulating layers around conductive media is dealt with. The authors aim at finding the best distribution of a fixed amount of insulation to be located around a conductive domain heated by an internal source. The problem is formulated both as topology optimization problem, i.e. seeking the layout of a fraction of insulating material, and as a shape design problem, i.e. distributing a thin layer of insulation. Both formulations may be actually seen as a preliminary approach for the achievement of the optimal layout of insulation around a fixed indoor environment with prescribed radiators.

More recently, Bruggi and Cinquini [26] have addressed the problem of maximizing the thermal insulation of buildings. The authors have developed an algorithm for minimizing the transmittance of walls, floors and ceilings, and to reduce the effects of undesirable thermal bridges. The procedure is based on the steady state heat equation, with boundary conditions of convective type.

The approach followed in the present work is similar to [26], but takes into account also the mechanical requirements that a